

New HST spectra indicate the QSO PG1718+4807 will not give the primordial deuterium abundance¹

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ABSTRACT

The $z_{\text{abs}} \sim 0.701$ absorption system towards QSO PG1718+4807 is the only example of a QSO absorption system which might have a deuterium/hydrogen ratio approximately ten times the value found towards other QSOs. We have obtained new STIS spectra from the Hubble Space Telescope (HST) of the Ly α and Lyman limit regions of the system. These spectra give the redshift and velocity dispersion of the neutral hydrogen which produces most of the observed absorption. The Ly α line is too narrow to account for all of the observed absorption. It was previously known that extra absorption is needed on the blue side of the main H I near to the expected position of deuterium. The current data suggests with a 98% confidence level that the extra absorption is not deuterium. Some uncertainty persists because we have a low signal to noise ratio and the extra absorption – be it deuterium or hydrogen – is heavily blended with the Ly α absorption from the main hydrogen absorption.

Subject headings: quasars: absorption lines – quasars: individual (QSO PG1718+4807)
– cosmology: observations

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1. Introduction

Only a few percent of QSOs have an absorption system which shows deuterium. Ground based spectra of most QSOs at redshift $z \sim 3$ show at least one absorption system having enough H I that the D I lines could be detected in spectra with resolution $\sim 10 \text{ km s}^{-1}$ and signal to noise ratio (SNR) ~ 50 . Such absorption systems always have enough H I to show Lyman continuum absorption and are called Lyman limit systems (LLS). Unfortunately, most LLS do not show deuterium because there is too much H I absorption near the expected deuterium position: -82 km s^{-1} towards shorter wavelengths from the H I. To date, only five systems at high redshift have been shown to either measure or to limit the primordial D/H abundance, and all agree with a value of $D/H = 3.0 \pm 0.4 \times 10^{-5}$ (D’Odorico, Dessauges-Zavadsky, and Molaro (2001), O’Meara et al. (2001), Kirkman et al. (2000), Burles & Tytler (1998a), Burles & Tytler (1998b)).

Several groups have tried to find deuterium in absorption systems at redshifts < 2 . This has the advantage that there is much less $\text{Ly}\alpha$ forest absorption at low redshift. However, most of the H I which hides deuterium may be associated with the main (LLS) hydrogen absorption, and it is not known whether such associated absorption becomes more or less common at lower redshifts.

Only one absorption system has been found at low redshift which might give the D/H ratio: QSO PG1718+4807, which is the subject of this paper. The reasons that we do not know of many more are that only about 30 QSOs are bright enough for 10 km s^{-1} spectra from the HST, and LLS are rare at low redshifts. The LLS at $z_{\text{abs}} \sim 0.7011$ towards QSO PG1718+4807 has the features expected of an absorption system which could show deuterium. It has a very steep Lyman limit (Lanzetta, Turnshek, and Sandoval 1993) and simple metal lines (Tytler et al. (1999), Webb et al. (1997)), both of which indicate that the H I may have a simple velocity structure. It also has a low metal abundance: $[\text{Si}/\text{H}] \simeq -2.4$ (Tytler et al. 1999).

Three groups have discussed one HST GHRS spectrum which covers the $\text{Ly}\alpha$ and Si III 1206 lines. Webb et al. (1997a, 1997b) noted that the $\text{Ly}\alpha$ line is asymmetric and can be fit with two symmetric Voigt profile components, separated by about 80 km s^{-1} . If the component on the lower wavelength side is entirely deuterium, then the entire $\text{Ly}\alpha$ line could arise from a single component, with $D/H = 20 \pm 5 \times 10^{-5}$. Levshakov, Kegel, and Takahara (1998) and Tytler et al. (1999) fit the same spectrum with single component H+D profiles, and found a wider range of $4.4 \times 10^{-5} < D/H < 57 \times 10^{-5}$ (95%). Tytler et al. (1999) also noted that all of the asymmetry could be explained by H I in a velocity component near -82 km s^{-1} , rather than D I, in which case D/H could not be measured in this absorber.

A variety of interpretations are possible because we have inadequate spectra of QSO PG1718+4807. First, the GHRS spectrum has low SNR: about 200 times fewer photons per km s^{-1} than the ground based spectra used to measure D/H. Second, the GHRS spectrum of QSO PG1718+4807 included just $\text{Ly}\alpha$ and one metal line. The D/H measurements which we have made in absorption systems at high redshift show 16 – 18 of the Lyman series lines and 5 - 20 metal lines. Both deficiencies mean that a wide range of parameters are allowed, and that it can not be determined if the extra absorption is deuterium or hydrogen. In this paper we present new HST STIS spectra of QSO PG1718+4807.

2. Observations and data reduction

Prior discussions of QSO PG1718+4807 utilized both space and ground based data. The space based data consisted of GHRS spectra covering the $\text{Ly}\alpha$ and SiIII lines of the LLS (Tytler et al. (1999), Webb et al. (1997), Levshakov, Kegel, and Takahara (1998)), in addition to IUE spectra which covered the Lyman limit (Lanzetta, Turnshek, and Sandoval 1993). The ground based data utilized the HIRES spectrograph on the Keck-I telescope (Tytler et al. 1999) to cover the wavelengths encompassing the MgII absorption of the LLS.

In this paper, we present new STIS spectra from HST which cover two regions crucial to the analysis of the D/H system towards QSO PG1718+4807: the $\text{Ly}\alpha$ line and the Lyman limit. We also present additional Keck HIRES spectra of the MgII absorption.

2.1. New HST STIS spectra of QSO PG1718+4807

We have two new sets of STIS spectra of QSO PG1718+4807: longslit FUV-MAMA observations and echelle NUV-MAMA observations. Here, we describe each type of observation, and in following sections, we discuss two instrumental issues which affect the data analysis, namely the STIS line spread function, and wavelength discrepancies between the STIS and GHRS spectra.

The STIS longslit exposures were taken using the FUV-MAMA detector through the $52 \times 0.2''$ slit and dispersed using the G140M grating. The total exposure time consisted of 11,327 seconds over four orbits on January 12 and 13, 1999. The spectra cover the wavelength range of 1540 – 1594 Å, with a pixel size of 0.0529 Å, and a resolution of 2.4 pixels FWHM. The exposures were processed using the standard CALSTIS pipeline. They were rebinned to a common wavelength scale then the weighted average was calculated. In terms of the QSO PG1718+4807 LLS, the longslit data cover the Ly-6 through Ly-18 transitions, and

wavelengths shortward of the Lyman limit. At the Lyman limit, the total signal to noise is approximately 8.5 per pixel. The final combined spectrum obtained from the long slit exposures is shown in Figure 1.

The STIS echelle exposures were taken using the NUV-MAMA detector through the 0.2x0.2" slit, and dispersed with the E230M echelle. The total exposure time consists of 14,131 seconds taken over five orbits on November 1, 1999. The spectra cover the wavelength range of 1871 – 2629 Å, with some spectral overlap between echelle orders. The pixel size was $\simeq 0.0336$ Å, with a resolution of 1.9 pixels, or a FWHM of 9.3 km s⁻¹. The echelle data cover the Ly α , SiIII, SiIV, and C IV transitions of the LLS. At the Ly α transition of the LLS near 2068 Å, the final SNR is approximately 5 per pixel. As with the longslit data, the data were processed using the CALSTIS pipeline, and were coadded in a similar fashion – the result is shown in Figure 2. We note that the version of CALSTIS used only a 1-D model for scattered light removal, which may result in flux errors of up to 3 % near the Ly α absorption. While there is now a 2-D version of the scattered light removal algorithm available from STScI, we have not used it on our data as our signal to noise is only 5. In both datasets, a local continuum was fit to the data by eye, using regions which were deemed to be free of absorption.

2.2. Line spread functions

When modeling the GHRS data, we used a Gaussian line spread function (LSF) with a FWHM of 14.1 km s⁻¹. Unlike the GHRS LSF, the STIS LSF can not be treated as Gaussian. Changes in the LSF cause significant differences in the measured velocity width of absorption lines and are of particular importance to our analyses. Thus instead of using a Gaussian LSF for the STIS observations, we use those provided by Sahu (2000) based on a combination of emission line spectra and theoretical simulations. The LSFs used in our analysis for the E230M and G140M gratings are shown in Table 1. We note that the true LSF may be slightly asymmetric, but that this asymmetry depends upon the orientation of the slit on the sky in a complicated way. After consulting with Sahu, we choose a symmetric LSF based on an averaging of the two sides to the STIS LSF for our analysis.

2.3. Wavelength calibration

Between the CALSTIS pipeline reduced STIS spectra presented here and the GHRS observations of QSO PG1718+4807 used in Tytler et al. (1999), there is a 0.08 Å or 12

km s⁻¹ difference in the observed wavelength of the Ly α transition of the LLS near 2068 Å. This difference was obtained via a cross-correlation of the two spectra over the common wavelengths covered, and confirmed by fitting profiles to several narrow absorption features present in both spectra.

The origin of this difference is unknown. It was corrected by shifting the GHRS spectrum to match the STIS data. We choose the STIS spectrum as the wavelength reference so that there would be consistency between the redshift scale used for the high order Lyman series lines and the Ly α absorption. We note that the STIS wavelengths for the redshift of the LLS agrees with the redshift of the MgII absorption from the HIRES data.

3. The absorption properties of the LLS at $z_{\text{abs}}=0.7011$

The new STIS data presented here cover the Lyman limit at high resolution for the first time and give additional spectra of the Ly α and metal line absorption. We discuss first the parameters describing the hydrogen followed by measurements and limits to the parameters describing the metal lines of the LLS, and then the metallicity, ionization, and thermal characteristics of the system.

3.1. Hydrogen Absorption

The STIS longslit data allow a good determination of the hydrogen absorption parameters present in the LLS towards QSO PG1718+4807. As illustrated in Figure 1, we fit the observed Lyman series transitions through to the Lyman limit, along with the residual flux blueward of 1554 Å. Also present in the spectrum is absorption due to Galactic C IV near 1548 and 1551 Å, which were not fit, as they did not affect the determination of the hydrogen parameters. All absorption features of interest were fit using Voigt profiles convolved with the LSF in Table 1.

From the STIS longslit spectra of the Lyman limit, we determine a column density of $\log N_{HI} = 17.22 \pm 0.005$ cm⁻², a velocity width of $b = 22.5 \pm 0.2$ km s⁻¹, and a redshift of $z = 0.701084 \pm (2 \times 10^{-6})$. This column density is consistent with that determined from the IUE spectrum of the Lyman limit (Lanzetta, Turnshek, and Sandoval (1993), Tytler et al. (1999)). The errors quoted represent only those random errors identified in the fitting procedure and do not include systematic errors. One such systematic error is the placement for the QSO continuum – particularly over the Lyman continuum absorption – which may be in error by a few percent.

The portion of STIS echelle spectra that covers the Ly α line of the LLS is shown in Figure 2 along with the prior GHRs data for comparison. The new STIS spectra have higher resolution, but lower SNR. In Figure 3, we show two fits to the observed STIS and GHRs spectra. The first fit shows the absorption due to hydrogen Ly α using the parameters determined from the Lyman limit STIS longslit data. This single absorber alone cannot fit all of the observed absorption on either the red or the blue sides of the line. The residual blue side absorption was previously known and is of primary interest, as it may or may not be caused entirely by deuterium absorption. The red side residual absorption is new result of this work. The results of the fits to the hydrogen are summarized in Table 2.

3.2. Metal line absorption

Also summarized in Table 2 are the parameters describing the metal lines seen in the LLS. The SiIII (1206) absorption is seen in both the GHRs and STIS spectra, and is shown in Figure 4. C IV is observed in the STIS echelle data, and is found to be consistent with the values derived from Tytler et al. (1999). The limit on the SiIV absorption comes from the STIS data presented here.

We re-observed the MgII absorption in QSO PG1718+4807 for an additional 5000 seconds with HIRES at Keck. The data were obtained using with the same setup and reduced in the way described in Tytler et al. (1999). The MgII absorption from the combined data set is shown in Figure 5. The line parameters from the combined data set are presented in Table 2.

3.3. The thermal state of the LLS

As with previous studies of D/H systems, we can use the metal line widths to estimate the thermal and turbulent velocity structure of the gas in the LLS. With this knowledge we hope to predict the velocity width of the deuterium absorption and compare it with the data to determine whether the observed absorption is consistent with deuterium. In ideal cases, all metal line widths are consistent with a single thermal and turbulent solution (e.g. O’Meara et al. (2001)). In the case of QSO PG1718+4807, however, we find inconsistent solutions.

There are two parts to the inconsistency: (1) The $b_{SiIII} \gg b_{MgII}$ such that both can not arise from the same gas and (2) the b_D predicted by the b_H and either the b_{SiIII} or the b_{MgII} is smaller than the extra absorption on the blue side of Ly α , $27.1 \pm 5.2 \text{ km s}^{-1}$. The

first inconsistency leads us to consider two models – one using just b_{SiIII} and the other using just b_{MgII} .

In one model, we use the measured velocity widths of the H I and SiIII absorption alone to determine a temperature of $T = 1.9 \times 10^4$ K and a turbulent velocity width $b_{turb} = 16.5$ km s⁻¹. This solution, shown by the upper dashed line in Figure 7, predicts $b_D = 19.2 \pm 0.84$ km s⁻¹, which is significantly smaller than the b value observed for the residual blue side absorption.

We also consider a second model in which the H I and MgII absorption are used to determine the turbulent and thermal properties of the gas, and it is the SiIII which resides in a second H I component. This model predicts a temperature of $T = 2.02 \times 10^4$ K and a turbulent velocity of 11.4 km s⁻¹. In this scenario, the predicted deuterium velocity width is $b = 17.2 \pm 0.5$ km s⁻¹, which is 1.9 σ lower than that observed for the extra blue side absorption.

We do not know which of the above scenarios is more likely, as we do not have a single ionization model which can account for all of the observed columns and b values. We can say with certainty, however, that if the extra absorption on the blue side of the LLS is D I, it must have a $b < 22.5$ km s⁻¹, which is the b value of the main H I absorption. It should be noted that in each of the previous five detections of D/H in a QSO absorption line system the deuterium width was significantly narrower than the hydrogen width because the H and D line widths were found to be consistent with almost pure thermal broadening. We would thus be quite surprised if the D absorption in this system has $b_D > 19.2 \pm 0.8$ km s⁻¹ – the maximum value plausible if the D/H absorption arises in the same gas as any of the observed metal lines.

We also note that because the MgII and SiIII do not have the same widths, there is probably more than one ionization state to this system. As a result, the ionization calculations done in Tytler et al. (1999) may give an accurate metallicity for the system.

4. Is the residual blue side absorption deuterium?

Given that the new STIS longslit data has specified the absorption parameters of the neutral hydrogen, we are now in a position to make a more critical assessment of the identity of the residual blue side absorption.

We define two simple requirements that the absorption must satisfy if it is deuterium. First, the gas must appear at the deuterium position relative to hydrogen in velocity space,

$v = -82 \text{ km s}^{-1}$. Second, the velocity width of the gas must be less than the hydrogen, i.e. it must have $b < 22.5 \text{ km s}^{-1}$, and we expect $b < 19.2 \text{ km s}^{-1}$. Our best fit parameters for the blue side absorption give a position relative to hydrogen of $v = -75.1 \pm 8.8 \text{ km s}^{-1}$ and a line width of $b = 27.1 \pm 5.2 \text{ km s}^{-1}$.

We wish to ascertain the likelihood that a D line with physically plausible parameters would cause us to measure the line parameters noted above. To do this, we step through a grid of velocity widths and relative positions for the extra absorption on the blue side of $\text{Ly}\alpha$. At each grid point we minimize the χ^2 of the model by varying the column density of the blue side absorber. In this way, we produce contours showing the probability that the data can be explained by a line at a given velocity with a given b -value. This contour plot is shown in Figure 7, with the contours at the 68.3%, 95.4%, 99.73% and 99.99% confidence levels.

From Figure 7, we again note that the most likely solution is marginally consistent with our two requirements for the absorption to be deuterium. All possible solutions consistent with our deuterium requirements are outside the 74% confidence interval from the most likely solution in the 2-D velocity/velocity dispersion space of Figure 7. We note that unless the velocity width of the deuterium is identical to the velocity width of the hydrogen the probability that the blue side absorption is not D is $> 74\%$. We also note that in the five D/H systems previously measured, the deuterium has always been significantly narrower than the hydrogen.

If we require the deuterium be consistent with the thermal parameters estimated from the SiIII and H I lines, i.e. $b_D = 19.2 \pm 0.8 \text{ km s}^{-1}$, the blue side absorption is not D at a 98% confidence level. Because no system has ever been observed with purely turbulent line widths, and because both the SiIII and MgII have significantly smaller line widths than the H I, we feel that $b_D = 19.2 \text{ km s}^{-1}$ is the highest likely b value for a deuterium line associated with this system. We thus conclude that the extra absorption is not D with a confidence $> 98\%$.

If instead the velocity width of the deuterium is consistent with the photoionization calculations and MgII+H I velocity widths, i.e. $b_D = 17.2 \pm 0.5 \text{ km s}^{-1}$, the deuterium only solution is less than 10^{-4} times as likely than the best solution describing the data.

We also investigated two component Hydrogen models for this system, under the assumption that the discrepant MgII and SiIII b values may indicate a more than one major component. We found that the total hydrogen absorption profile is well constrained by the high order Lyman series lines, and as a result introducing a multi-component hydrogen model does not increase the likelihood that the extra blue side absorption is deuterium.

5. Discussion

This system has received extensive consideration because it was thought to be possible that it would provide evidence for a very high D/H ratio, in contrast to lower values of D/H found in all other QSO absorption systems. The absorption system was believed to be a single component system, which would have indicated that the extra blue side absorption was D.

However, now that we have properly constrained the main hydrogen absorption through profile fitting of its high order Lyman series lines, it now appears likely that there is contaminating absorption on the blue side of the LLS. This conclusion is supported by the fact that no physically plausible D line can explain the data and that there is also extra absorption on the red side of the system. Since the red absorption can not be deuterium, it indicates the LLS has the type of complex velocity structure that can easily produce extra absorption outside of the main component.

We thus conclude that this is a multi component absorption system which likely has unconstrained absorption near the expected position of deuterium, and that no determination of the primordial D/H ratio can be obtained from QSO PG1718+4807 with data available at this time.

6. Acknowledgments

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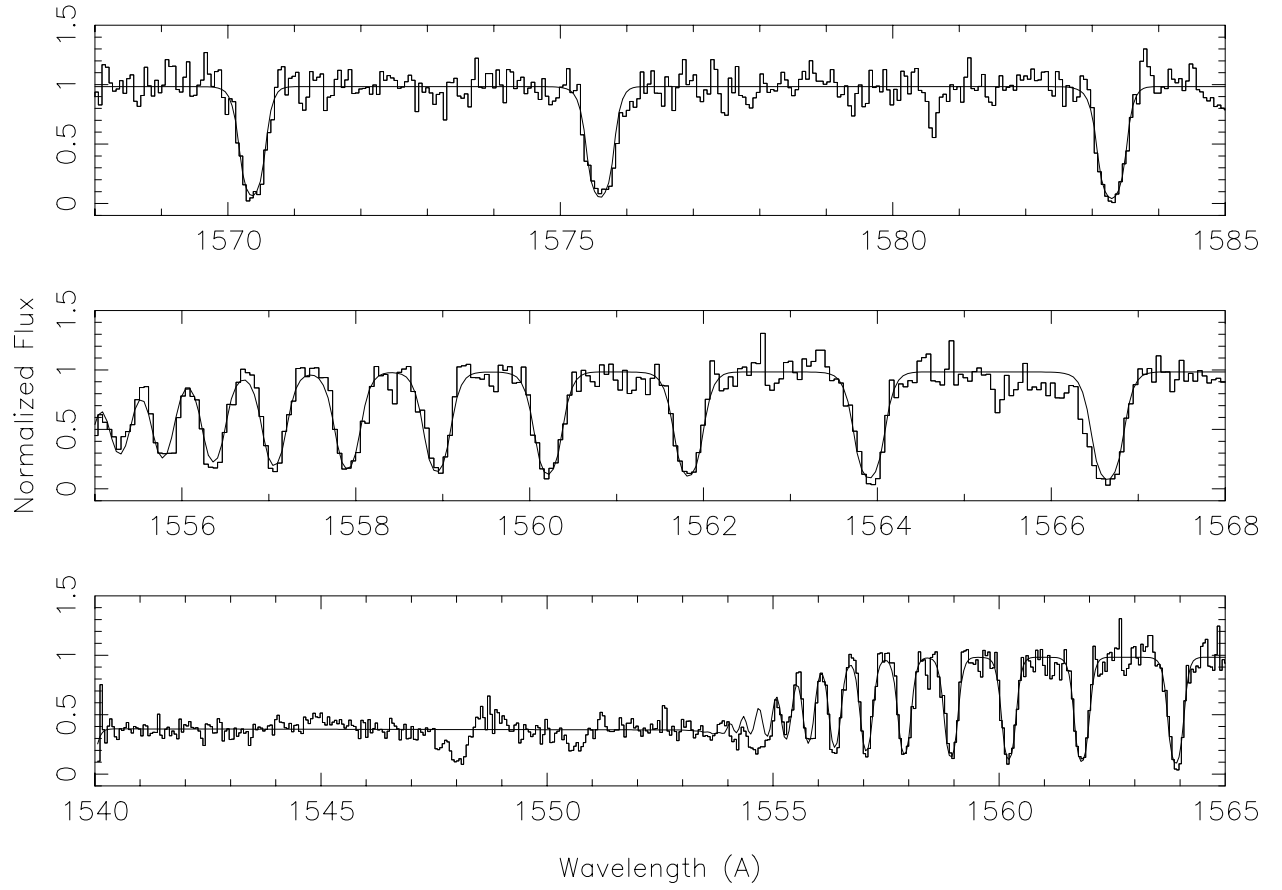


Fig. 1.— STIS G140M spectrum of the Lyman limit region of QSO PG1718+4807. The smooth line is our best fit solution to the hydrogen absorption.

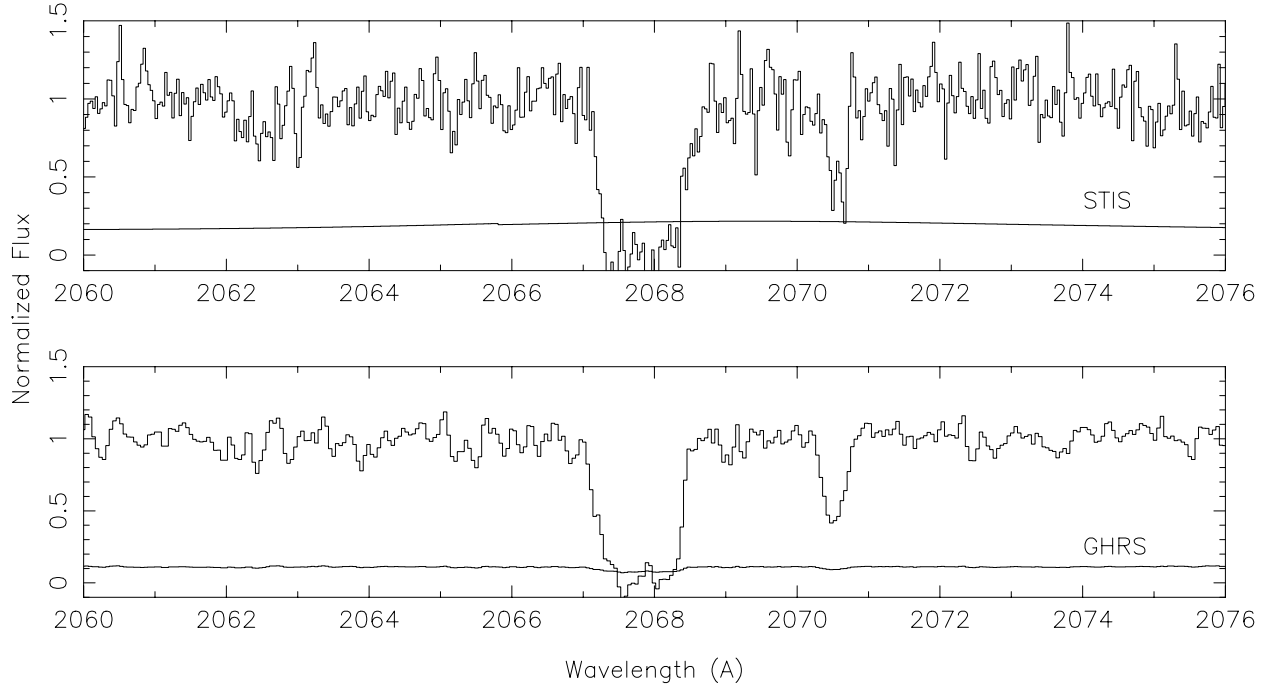


Fig. 2.— The absorption at ~ 2068 Å is $\text{Ly}\alpha$ at $z_{\text{abs}} = 0.7011$ seen in the STIS E140M (top, 9.3 km s^{-1} FWHM) and GHRS (bottom, 14.1 km s^{-1} FWHM) spectra of QSO PG1718+4807. A long stretch of spectra is shown to demonstrate the quality of the data. The line near 0.1 indicates the error on the normalized flux in each pixel in the spectrum.

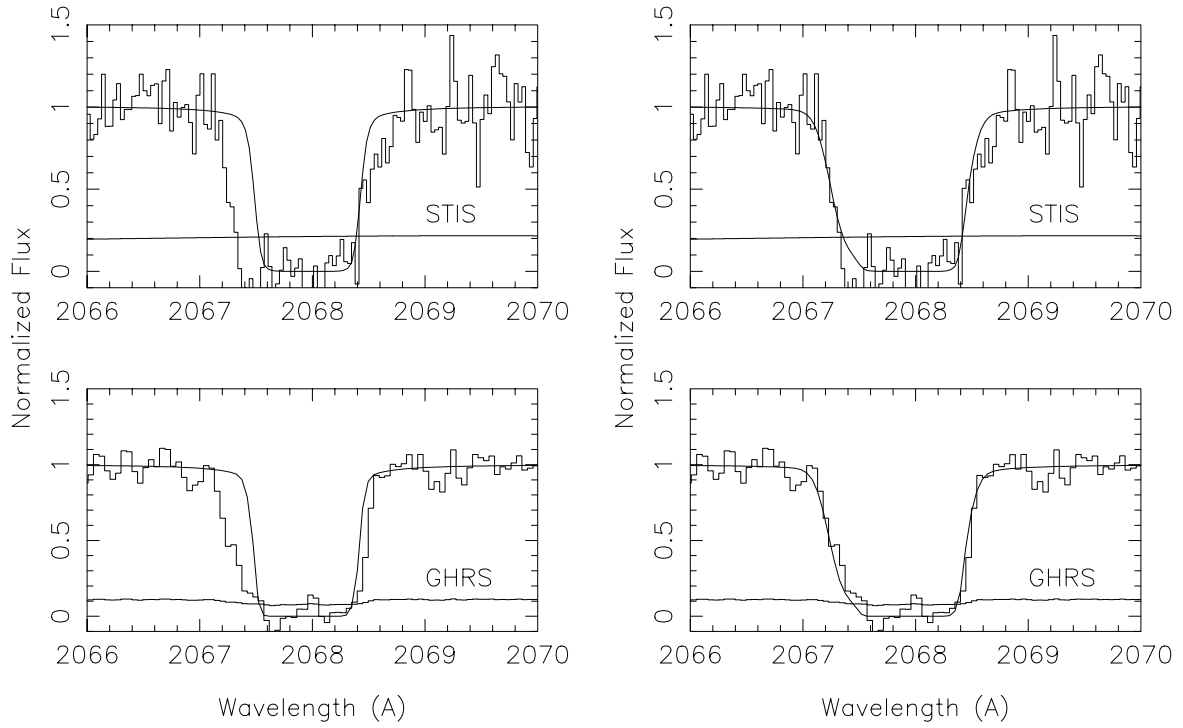


Fig. 3.— The $\text{Ly}\alpha$ absorption line in the STIS and GHRS spectra. The left hand panels show the expected H I absorption from the fit to the Lyman limit. The right hand panels show our full model to the data, summarized in Table 2.

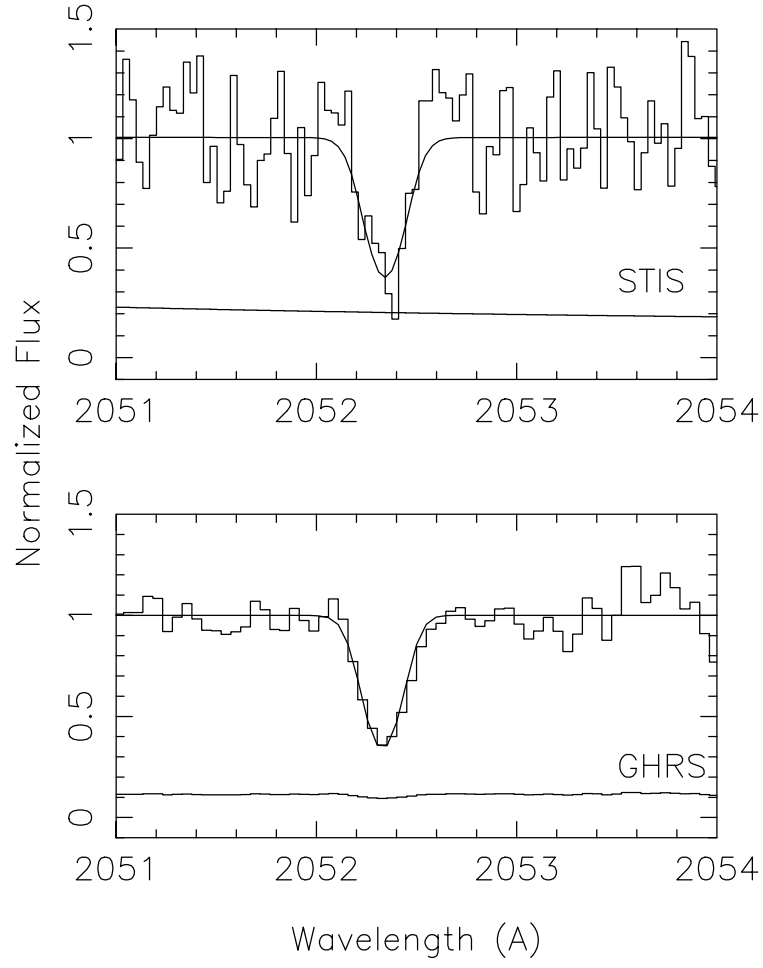


Fig. 4.— The observed SiIII (1206) absorption in the STIS and GHR spectra, along with the single best fit to both.

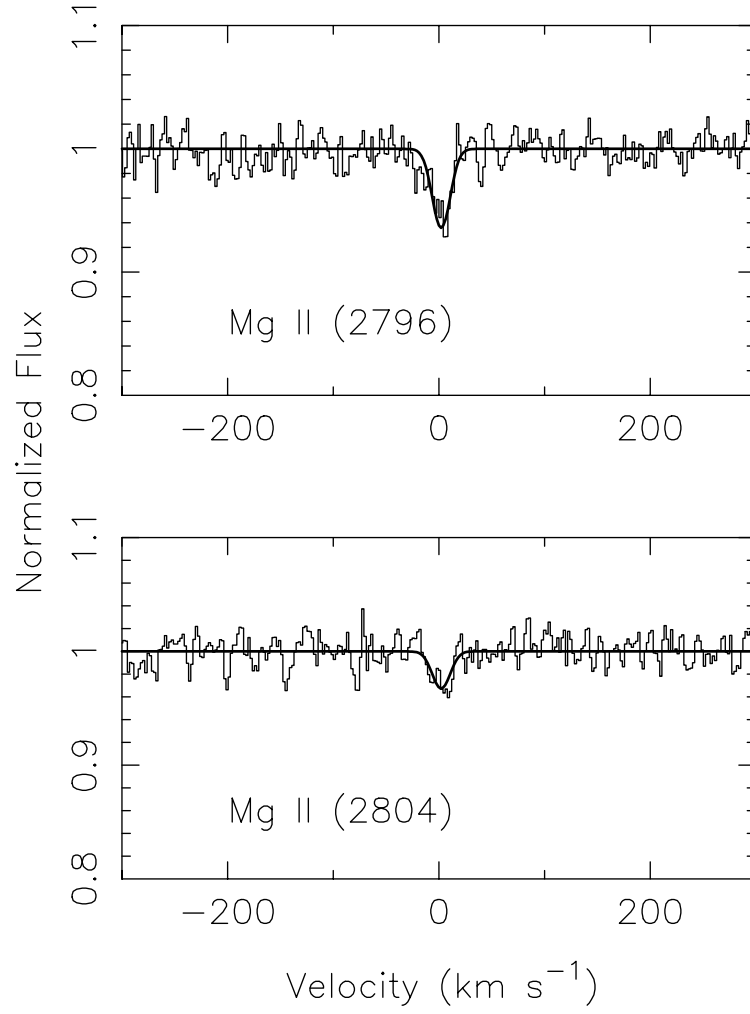


Fig. 5.— The MgII absorption in the Keck HIRES spectra. The velocity zero point is the redshift of the hydrogen LLS, $z_{\text{abs}} = 0.701084$.

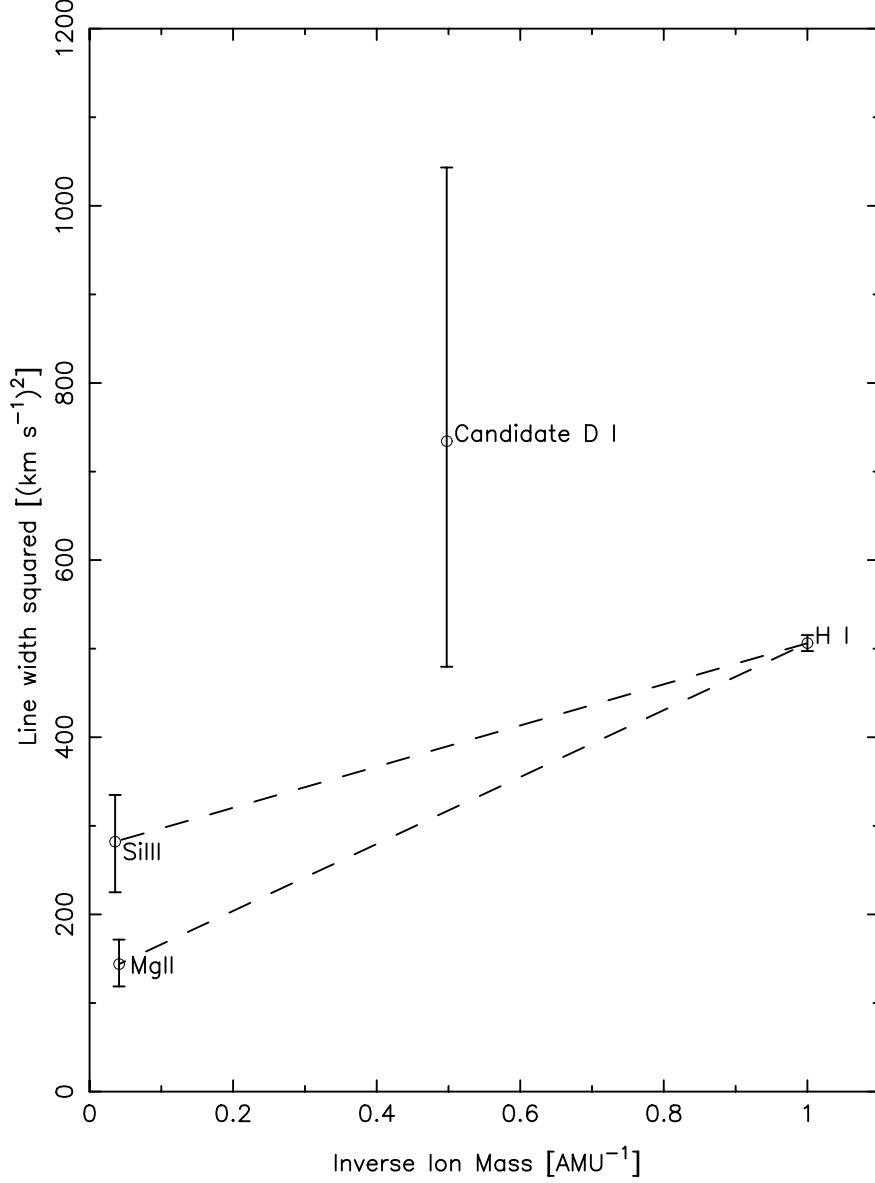


Fig. 6.— The line widths of the observed ions. If all of the absorption came from the same gas, all of the points should lie on a straight line. The fact that H I, SiII and MgII do not lie on a straight line indicates that the system contains more than one thermal state (or measurement errors). If either the MgII or the SiIII comes from the gas showing H I, then the residual blue side absorption (here marked ‘candidate D I’) is wider than expected for D.

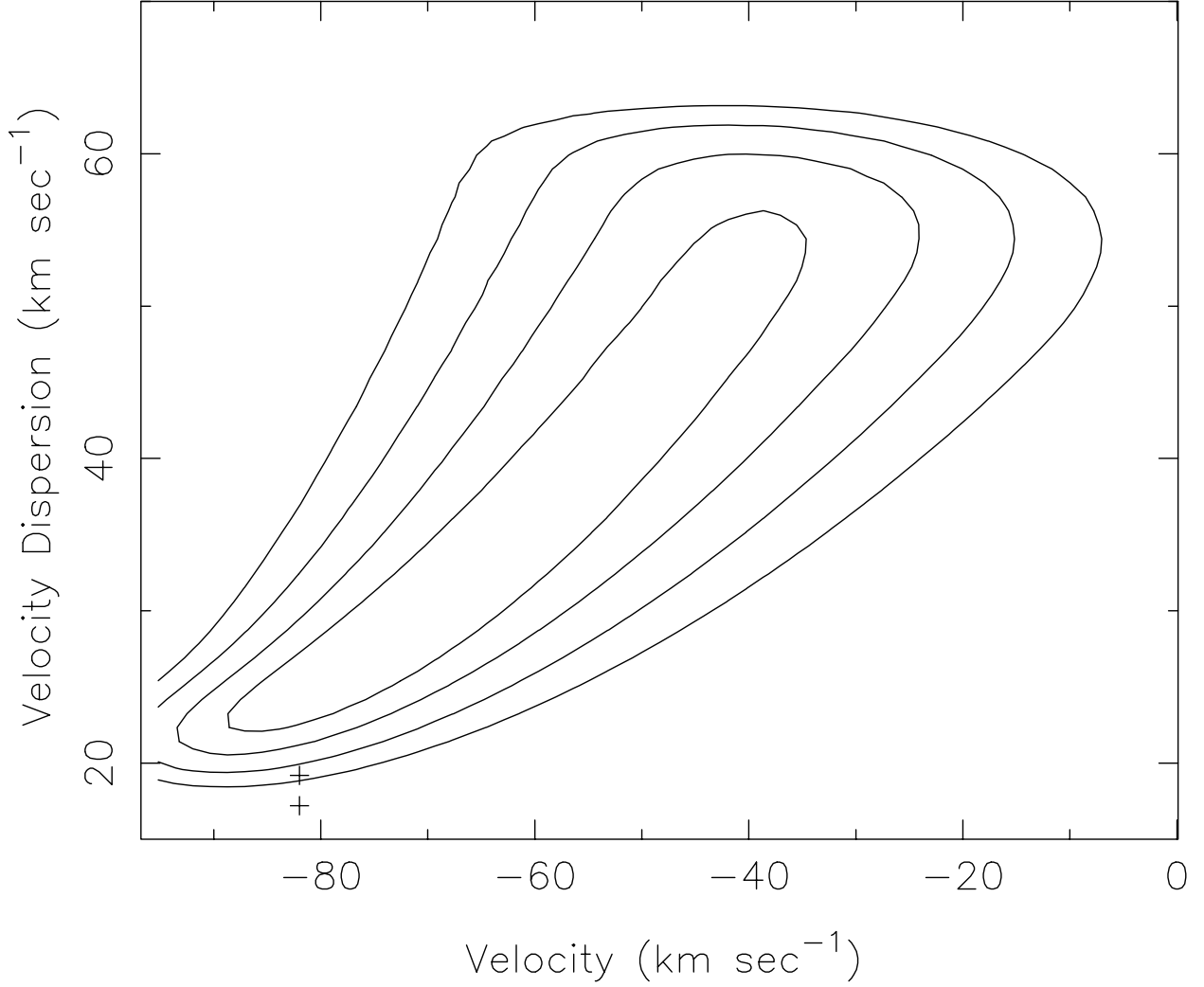


Fig. 7.— Probability that the blue-side absorption has a given velocity dispersion and redshift. The contour levels show the 68.3%, 95.4%, 99.73% and 99.99% confidence levels based on differences in χ^2 of 2.3, 6.17, 11.8 and 18.4 from the best fit solution. The two marked points mark the location in parameter space of possible D lines – the point at $b = 17.2$ km s⁻¹ is the D line expected if the H I and MgII absorption arise in the same gas, and the $b = 19.2$ km s⁻¹ point is the D line expected if the H I and SiIII absorption arise in the same gas.

Table 1. STIS normalized line spread functions

Pixel	e230	g140m
0	0.3765	0.3059
1	0.2201	0.1702
2	0.0589	0.0849
3	0.0204	0.0564
4	0.0080	0.0192
5	0.0030	0.0093
6	0.0013	0.0048
7		0.0022

Table 2. Lines observed in the $z_{\text{abs}} \sim 0.7011$ LLS

Ion	$\log(N)$ (cm^{-2})	b (km s^{-1})	z	velocity (km s^{-1})	$\sigma_{\log(N)}$	σ_b	σ_z	σ_v
H I	17.23	22.5	0.701084	0	0.005	0.2	2e-6	0.35
H I	13.47	22.2	0.701406	56.7	0.8	13.1	1e-4	16.1
H I ^a	13.84	27.1	0.700658	-75.1	0.14	5.2	5e-5	8.8
SiIII	12.85	16.8	0.701062	-2.1	0.04	1.8	8e-6	1.4
MgII	11.5	12.0	0.701100	2.8	0.05	1.1	5e-6	0.88
SiIV ^b	< 12.6	–	–	–	0.1	–	–	–

^aPossibly Deuterium

^bNot detected